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Binding Energies and Lifetimes of Lighter Hyperfragments

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In an emulsion stack exposed to a stopping K^- beam at the Bevatron, we have observed hyperfragments in order to make lifetime and binding-energy measurements on the lighter hyperfragments formed. We have measured the binding energies of 28 hyperfragments with mass number $7 \leq A \leq 13$. Restricting ourselves to lifetime measurements using the $\pi^- pr$ decay modes, we observed three decays in flight, one each of ${}_\Lambda H^3$, ${}_\Lambda He^4$, and ${}_\Lambda Li^7$. Combining our ${}_\Lambda He$ data with previous measurements, we obtained the lifetime $({}_\Lambda He) = (1.9_{-0.4}^{+0.6}) \times 10^{-10}$ sec for the ${}_\Lambda He$ group. This value is slightly more than one standard deviation less than the predicted values for ${}_\Lambda He^4$ and ${}_\Lambda He^5$.

INTRODUCTION

THE measurements of binding energies of the hyperfragments with mass $A \geq 7$ are limited in their accuracy due to the limited numbers of identified hyperfragments. In the case of some species, particularly those with mass $A \geq 10$, the number of observed events is relatively small. A sample of such hyperfragments is reported on in this paper.

In addition, the lifetimes of the hyperfragments are predicted by Dalitz and Rajasekharon[1] and have been measured in previous experiments.[2–8] The total data accumulated has given lifetimes with a large uncertainty due to the relatively small amount of flight time observed. Additional information on lifetimes has beeen obtained.

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EXPERIMENTAL PROCEDURE

A stack of 100 Kodak K-5 emulsion pellicles, each of sizes 15 cm$\times$10 cm$\times$0.07 cm, was exposed at the Bevatron to a stopping K^- beam. An area scan has been made of the 45 interior plates which contained the largest incident K^- flux in order to minimize the number of decay pions which left the stack and still get a large stopping K^- sample. The total number of K^- captures observed was $\sim$35 000. The area scan was performed with a magnification of 125$\times$. All gray and black prongs from each capture were traced under a magnification of 530$\times$ to their ends or until they left the pellicle by the scanners. The recorded K^- captures were then re-examined by a second observer who again traced all black and gray tracks to their ends or their point of leaving the pellicle.

The observed mesonic decays of hyperfragments were measured using a cyclops with calibrated eyepiece to measure the projected and dip angles of the hyperfragment and its decay products. The short ranges were also measured using the measuring eyepiece and longer ranges were measured using dial gauges mounted on the microscope stage. The dip angle was then calculated by the least-squares fit of the data to a straight line. This analysis of the data was done by a modified version of program RANG.[9] In addition to measurements of the hyperfragment decays a sample of 70 $\Sigma^+ \rightarrow p + \pi^0$ decays at rest were examined and the protons measured to determine the range-energy calibration of the

[9] Original RANG was written by E. N. Shipley at Northwestern University.

emulsion. The measurements indicated the average proton range to be 1730±3 μm indicating that the emulsion was of significantly lower density than standard emulsion in which the average proton range from Σ^+ decays at rest is 1676 μm. Since the calibration correction for variation in density from the standard values varies significantly with the value of β for a particle, it was decided to make the approximate correction implied by the proton measurement and to identify all π-proton-recoil decays by analysis of the momentum balance using the computer program for hyperfragment analysis, HANK.[10] When the identities were known, a sample of 49 uniquely identified events ${}_{\Lambda}He^5 \rightarrow \pi^- + p + He^4$ was selected and the true pion ranges were determined by correcting the pion ranges in this sample to a value so that the average binding energy of the ${}_{\Lambda}He^5$ sample was 3.23 MeV in agreement with the previous measurements.[11–13] This yielded a correction of 2.6% required for all pion ranges in the range from approximately 10 to 30 mm, where most of our decay pion ranges were. The correction for all proton and heavier particle ranges was made by the use of the $\Sigma^+ \rightarrow p + \pi^0$ data and a curve fitted to the graph of range correction versus β of the particle.[14]

TABLE I. Heavy hyperfragment summary.

	Event No.	E_π (MeV)	Type	Recoils (μm)	B (MeV)	R_{HF} (μm)
${}_{\Lambda}He^7$	1-25-1	30.15	πpr	5.73	2.78	22.7
	1-42-2	28.93	πpr	3.67	4.21	10.9
	1-58-7	30.89	πpr	4.02	3.88	111.7
	1-59-1	30.82	πpr	3.02	2.82	13.0
	1-68-4	31.47	πpr	5.45	4.26	8.1
					Ave. 3.59	
${}_{\Lambda}Li^7$	1-27-5	36.70	πr	1.3	5.80	34.1
	1-35-7	25.70	$\pi^- p\alpha d$	5.2, 12.5	6.00	11.3
	1-66-1	37.17	πr	1.7	5.33	11.0
					Ave. 5.71	
${}_{\Lambda}Li^8$	1-29-2	43.89	$\pi\alpha\alpha$	10.1, 3.8	7.54	10.5
	1-36-1	33.94	$\pi\alpha\alpha$	60.0, 24.5	6.21	29.0
	1-43-4	41.62	$\pi\alpha\alpha$	12.2, 10.5	7.52	4.6
	1-47-3	48.10	$\pi\alpha\alpha$	3.3, 0.3	6.22	2.9
	1-52-7	46.93	$\pi\alpha\alpha$	5.6, 2.7	6.05	24.2
	1-61-1	43.12	$\pi\alpha\alpha$	13.9, 5.6	6.89	13.0
	1-70-1	37.27	$\pi\alpha\alpha$	38.8, 10.9	7.62	6.8
	1-55-3	43.14	$\pi\alpha\alpha$	17.9, 2.6	7.14	5.8
	1-52-5	25.24	πpr	3.0	7.09	29.4
					Ave. 6.93	
${}_{\Lambda}Be^8$	1-32-6	27.24	πpr	1.7	6.72	9.0
${}_{\Lambda}Be^9$	1-25-2	24.74	$\pi p\alpha\alpha$	8.9, 5.9	7.52	37.3
	1-51-4	28.34	$\pi p\alpha\alpha$	2.4, 2.2	6.25	3.0
					Ave. 6.88	
${}_{\Lambda}Be^{10}$	1-30-8	35.48	πr	1.0	8.29	5.1
	1-42-6	27.03	$\pi\alpha Li^6$	2.8, 6.4	9.85	5.5
					Ave. 9.07	
${}_{\Lambda}B^{11}$	1-29-7	25.72	$\pi\alpha Be^7$	9.75, 1.0	10.12	3.3
	1-33-2	36.24	πr	0.2	9.69	1.5
					Ave. 9.90	
${}_{\Lambda}B^{12}$	1-36-3	29.39	$\pi\alpha\alpha\alpha$	16.6, 3.7, 2.9	11.34	16.5
	1-58-6	42.73	πr	0	10.42	7.7
					Ave. 10.88	
${}_{\Lambda}C^{13}$	1-28-11	29.24	πr	0.5	10.10	2.9
	1-36-8	27.55	πr	0.1	11.82	6.3
					Ave. 10.96	

In the case of the events used for lifetime measurements it was necessary in some cases to determine the charge of hyperfragments after the decay analysis. Usually this was necessary because of the short recoil for the $\pi^- pr$ decay mode could not be uniquely identified by momentum considerations. The charge determinations were made using track thickness measurements on the unknown tracks and by comparison with ${}_{\Lambda}H$ and ${}_{\Lambda}He$ tracks which were known from kinematic decay analysis,

Production star analysis was used in some cases to assist in uniquely identifying the decays of heavier hyperfragments which were produced by K^- captures on C^{12}, N^{14}, or O^{16}.

Decays in flight were only considered as identified if the analysis of the decay implied a momentum for the hyperfragment ≥60 MeV/c in the incident direction of the hyperfragment. Also, the implied binding energy was required to be within experimental uncertainty of the accepted value for the species. The lower limit on the momentum value was required due to the momentum unbalances which typically occur because of the uncertainty in the momenta of the recoils in $\pi^- pr$ decays.

BINDING ENERGIES OF HYPERFRAGMENTS WITH $A \geqslant 7$

Table I gives information for the hyperfragment decays observed which were uniquely identified. Other events observed did not have a unique identity due to the shortness of one of the decay prongs and the impossibility of primary star analysis. The five uniquely identified decays of ${}_{\Lambda}He^7$ by the $\pi^- pr$ decay mode were all of relatively low B_Λ (<4.3 MeV), giving no indication of the isomeric state of ${}_{\Lambda}He^7$.[15]

In the case of the decays of heavy hyperfragments by the π^- pr and $\pi^- r$ modes the possibility exists of the emission of heavy recoils in excited states, decreasing the visible energy emitted in the decay prongs. This complicates the identification of hyperfragments decaying by the common $\pi^- r$ mode. Figure 1 shows the expected π^- energies emitted in $\pi^- r$ decays of heavier hyperfragments and it also indicates the π^- energies

[10] HANK is the hyperfragment analysis kinematics program of R. G. Ammar of Northwestern University.

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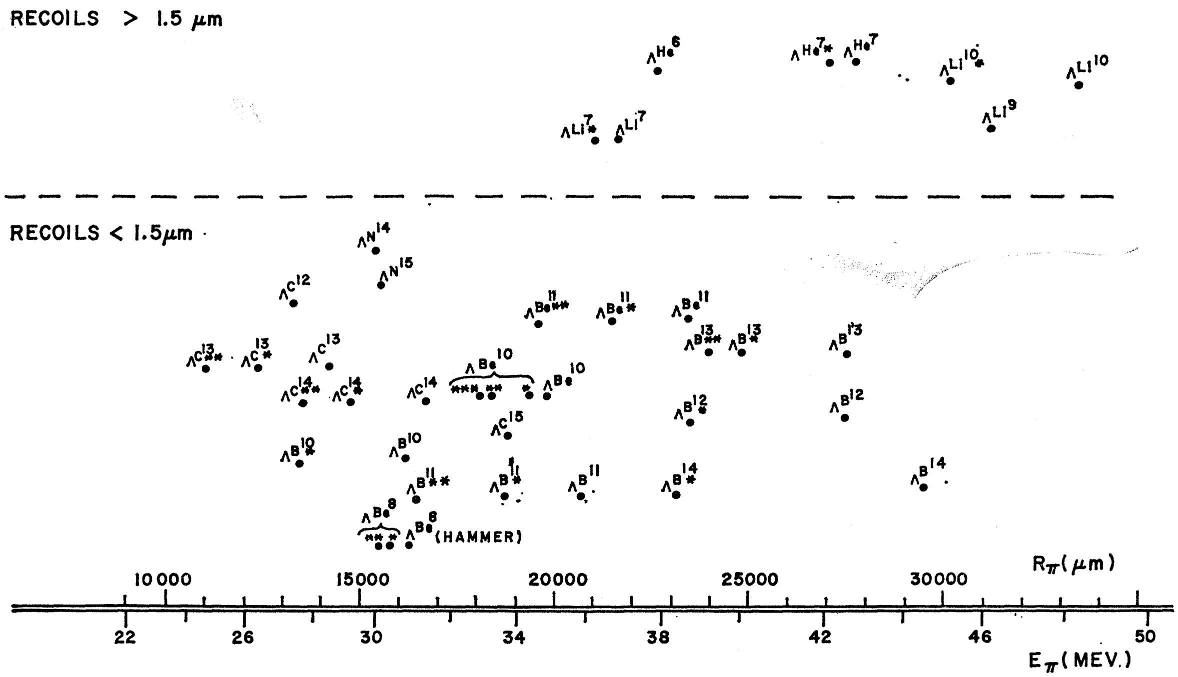

FIG. 1. Expected π^- ranges and energies for π^--recoil decay modes. For species which have not been observed ranges are based on estimates of expected binding energies for these species used previously (Ref. 11).

expected if the recoils emitted are in lower excited nuclear states. The hypernuclei with one * decay with the recoil in the first excited state, those with ** into the second recoil excited state, etc.

Events 1-27-5 and 1-66-1

In the case of $_\Lambda Li^7$, the recoil is too long to be $_\Lambda B^{10}$, $_\Lambda Be^{10}$, $_\Lambda Be^{11*}$, but $_\Lambda He^6$ which has never been detected is a possible identity.

Event 1-30-8

The short recoil and π^- energy indicate $_\Lambda Be^{10}$, $_\Lambda B^{11}$, $_\Lambda C^{15}$, or $_\Lambda Be^{11*}$. The short hyperfragment range implies a capture on a light element and the number of production prongs imply that the hyperfragment charge is ≤ 4. $_\Lambda Be^{10}$ has been observed but $_\Lambda Be^{11}$ has not been detected.

Event 1-33-2

The short recoil and π^- energy indicate $_\Lambda Be^{11*}$ or $_\Lambda B^{11}$. $_\Lambda Be^{11}$ has not been observed and thus the decay of $_\Lambda Be^{11}$ through an excited recoil is not a likely identity.

Event 1-58-6

The large π^- energy implies $_\Lambda B^{12,13}$, but the production has three heavy prongs and a pion in addition to the hyperfragment. Kinematics imply that $_\Lambda B^{13}$ is not possible because $K^- + O^{16} \rightarrow {}_\Lambda B^{13} + p + p + p + \pi^-$ does not balance momentum.

Events 1-28-11 and 1-36-8

These events are in best agreement with $_\Lambda C^{13} \rightarrow \pi^- + N^{13}$. Event 1-28-11 could be $_\Lambda C^{14*}$ except that production kinematics rule out this possibility. Event 1-36-8 could be $_\Lambda C^{12}$ or $_\Lambda C^{14**}$ which are not ruled out by the primary star considerations, but neither of these decay modes have been identified previously.

LIFETIME MEASUREMENTS

In our sample of hyperfragments which decay by the mesonic mode, we measured each event and subjected them to the decay kinematic analysis of program HANK. The program first attempted to fit the event to the $\pi^- p r$ decay scheme. If this was not successful, the identity of all prongs except the π^- was permutated trying all isotopes of H, He, and Li (except Li^8 which would be detected by a "hammer" decay). All possible decay modes were kinematically tested for momentum and energy balance. In each case assuming the momentum unbalance to be that of an additional neutron emitted in the decay, the energy balance was calculated for one-neutron decay modes.

If an event either through the orientation of the decay prongs or characteristics of the hyperfragment track appeared to be a possible decay in flight the possibility of a decay in flight was tested by HANK by comparing the hyperfragment track direction with the direction of the decay prong momentum unbalance and also by checking the energy balance when the hyperfragment

TABLE II. Decays in flight.

Event	Indentity	HF range (μm)	HF momentum at decay (MeV/c)	Time of flt. (sec)
1-51-7	$_\Lambda He^4$	19.1	173	1.8×10^{-12}
1-66-2	$_\Lambda H^3$	353.0	184	14.4×10^{-12}
1-67-1	$_\Lambda Li^7$	42.4	88.5	3.2×10^{-12}

was assigned a momentum equal to the calculated momentum balance.

In our sample of data, we have observed three events which are decays in flight of hyperfragments, $_\Lambda H^3$, $_\Lambda He^4$, and $_\Lambda Li^7$. The data on these events are given in Table II. We have restricted our search to events decaying by the πpr mode, since the πr decay modes of $_\Lambda H^{3,4}$ may be more difficult to detect in flight than at rest introducing a bias into the result.

In the case of $_\Lambda H^3$ a significant amount of data has been accumulated using various methods.[2,4–8] We have not examined our data further in the case of $_\Lambda H^3$. In the case of $_\Lambda$He, we have a sample with identified $_\Lambda He^4$, $_\Lambda He^5$, $_\Lambda He^7$, and ambiguous $_\Lambda He^{4,5,7}$ events.

In the case of $_\Lambda$Li and $_\Lambda$Be hyperfragments the problem of identifying πpr decay modes is difficult because the average recoil momentum is small enough to make the recoil too short to measure accurately and identify uniquely. If one uses the binding energy to assist in separation of the πpr decay modes one can identify a sample of πpr decays of the group $_\Lambda Li^{7,8}$ and $_\Lambda Be^8$ reasonably well. The detection of decays in flight also presents a problem as backward emission of the recoil in the center-of-mass system can result in a short prong in the laboratory system which hinders identification of the decaying hyperfragment. Because of the detection difficulty for the decays in flight the resulting lifetime could only be considered as an upper limit.

TABLE III. Flight time data.

A. $_\Lambda$He	No. at rest	No. in flight	Total flight time (10^{-12}sec)
$_\Lambda He^4$	11	1	66
$_\Lambda He^5$	41	0	222
$_\Lambda He^7$	5	0	27
$_\Lambda$He	34	0	221
Total	91	1	526

Total (corrected for $P_{HF}\geq 60$ MeV/c and $R_{HF}\leq 20$ μm) $=517\times10^{-12}$ sec.

B. Li, Be. No. at rest = 10; No. in flt. = 1

Total flight time corrected for $P_{HF}=60$ MeV/c and assuming all events to be

$_\Lambda Li^7$	22×10^{-12} sec
$_\Lambda Li^8$	24×10^{-12} sec
$_\Lambda Be^8$	18×10^{-12} sec

The numbers of events and total flight times observed for $_\Lambda$He and $_\Lambda$Li-$_\Lambda$Be are recorded in Table III. In the case of $_\Lambda He^{4,5}$ work in the past [3,6–8] has indicated lifetimes somewhat shorter than predicted by theoretical calculations.[1] The sample of events from Ammar *et al.*, Kang *et al.*, Prem and Steinberg, and the present work can be used as a group to obtain a combined value for the $_\Lambda He^{4,5}$ lifetime prediction. In this case we have made the calculation using the total values of the various flight times and numbers of events and made a single calculation for the average lifetime. Using the Bartlett maximum likelihood relation[16] and the method of Franzinetti and Morpurgo,[17] one obtains from these pieces of data a value of the average lifetime of $(1.9_{-0.4}^{+0.6})\times10^{-10}$ sec., based on a total of 18 flight decays and 345 decays at rest in the $_\Lambda$He sample. The predicted lifetimes given by Dalitz and Rajasekharon are: $\tau(_\Lambda He^4, \text{spin } 0)=1.02\tau_\Lambda$ and $\tau(_\Lambda He^5, \text{spin } \frac{1}{2})=1.15\tau_\Lambda$. Using $\tau_\Lambda=2.51\times10^{-10}$ sec,[13] the predicted lifetimes become $\tau(_\Lambda He^4, \text{spin } 0)=2.56\times10^{-10}$ sec, and $\tau(_\Lambda He^5, \text{spin } \frac{1}{2})=2.89\times10^{-10}$ sec. Comparison indicates that the predicted values are slightly greater than one standard deviation above the measured value.

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